AD A074504

LEVEL II

CR 79.010

CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND

QUANTIFICATION OF EXPLOSION PROBABILITIES FOR NAVY TIDEWATER SCENARIOS

April 1979

An Investigation Conducted by
J. H. WIGGINS COMPANY
Redondo Beach, California

N68305-78-C-0051

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: CR-79.010	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): QUANTIFICATION OF EXPLOSION PROBABILITIES FOR NAVY TIDEWATER SCENARIOS		5. TYPE OF REPORT & PERIOD COVERED: Final April 1979
		6. PERFORMING ORG. REPORT NUMBER: 79-1343
7. AUTHOR(s): Jon D. Collins, Jerold Haber		8. CONTRACT OR GRANT NUMBER(s): N68305-78-C-0051
9. PERFORMING ORGANIZATION NAME AND ADDRESS: J.H. Wiggins, 1650 So. Pacific Coast Highway, Redondo Beach, CA 90277		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: YF53.534.091.01.411
11. CONTROLLING OFFICE NAME AND ADDRESS: Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, CA 93043		12. REPORT DATE: April 1979
		13. NUMBER OF PAGES: 61
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Naval Facilities Engineering Command, 200 Stovall Street, Alexandria, VA 22332		15. SECURITY CLASS (of this report): Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Explosives Safety; Explosion Probability; Tidewater Hazards; Risk

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents results of an initial effort to establish a procedure for estimating the probability of occurence of all possible yields of inadvertent explosions in the Navy tidewater hazard scenario. The procedure is intended for ultimate use in a risk-decision model that will aid the Navy in the management of risk at activities supporting the ammunition logistics system.

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Block 20. Abstract Cont'd

The procedure involves first constructing an ordnance logistical sequence diagram that simulates the sequence of events composing each type of possible ordnance transaction. Each event in the diagram is an opportunity for a mishap that could lead to a detonation or fire. The probability of occurrence of possible mishaps in each event is derived from historical records of mishaps. The conditional probabilities of an explosion (given a mishap) and sympathic communication of an explosion to other stores of ordnance are based on scientific and historical data base. The mathematical approach allows for the use of Bayesian statistics when the data base is inadequate and keeps track of uncertainty in the predictions.

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SUMMARY

This report recommends a methodology for estimating the probabilities and yields of accidental explosions at Naval shore facilities. Considerations that are included are the activities involving the maintenance of ordnance, the probability of fires and initiation from fires, and the sympathetic detonation of explosives.

The mathematical approach allows for the use of a Bayesian methodology when the data base is inadequate. A methodology is also included for synthesizing the event probabilities so that lists of ordnance locations can have probabilities of explosions for various yields. The methodology also keeps track of uncertainty in the predictions.

1. INTRODUCTION

The purpose of this study is to establish a rational basis for determining the source, size and frequency of inadvertent explosions resulting from the maintenance, storage and transfer of ordnance at the Navy Tidewater. This is the first step in moving the procedures used to regulate construction and location of personnel from a deterministic to a probabilistic (calculated risk) basis. For years, explosives safety quantity distance (ESQD) tables, relating charge weight to safe separation distance (derived from historical records of accidental explosions) have been used to determine the spacing of ships at port, the positioning of inhabited structures and the locating of personnel. These ESQD tables do not consider the likelihood of an explosion, but rather the protection required given an explosion. If land were not limited, or had no cost, this would be a proper approach. However, because of land limitation and cost, Navy bases have had to encroach upon the area identified as hazardous by the ESQD tables. To do this, waivers of the ESQD distance have been obtained with no knowledge of the additional risk being accepted as a result of unavoidable deviations from established safety standards.

Since the current deterministic approach to explosion safety at the waterfront has created a situation of many waivers and unknown risk, a new methodology must be introduced which determines the risk of any deviations from established safety standards and can provide guidelines for minimization of risk in future expansion or modification at the Tidewater. The methodology presented in this report is to provide a basis for the risk computation, .. namely, estimating the source, size and frequency of explosions resulting from ordnance operations. The methodology provides an estimate of the probability, and uncertainty in the estimate, of an accidental explosion resulting from a handling mishap, fire mishap, or the storage and spacing of explosives. It is understood that the methodology must be developed with a minimum of impact on current Navy procedures. It must be rational, reasonable and do-able, and must also acknowledge uncertainty and quantify that uncertainty wherever it exists. The methodology that is presented in the following sections of this report attempts to satisfy these requirements.

2. THE TIDEWATER SCENARIO

Before the discussion of the model, it is important to describe a typical tidewater scenario* in order to give the reader a perspective of the variety of operations and the various elements which must be considered in establishing the probability of an explosion of ordnance. For this discussion, a submarine base was chosen which consisted of the following elements:

(1) A pier with a submarine tender moored alongside,

(2) A submarine alongside the tender,

(3) A submarine alongside the pier,

(4) A magazine on shore for storage of warheads,

(5) A shop for maintenance and checkout of torpedoes.

A typical sequence of activities for the movement of a fused MARK 48 torpedo from the tender to the torpedo shop and then back to the submarine is shown in Figure 2-1. An attempt has been made in this figure to detail each new activity in the transfer process. Henceforth, these individual and unique activities will be defined as links in the transfer process. It would be possible to take each of the ordnance handling activities at the base and characterize them in sequential processes as demonstrated in Figure 2-1. This would then provide an analyst of risk with fine detail on all of the procedures and actions in the handling of ordnance. If accurate statistics were available on the probability of a mishap in each one of these links, it would be a simple matter to construct the probabilities of various explosive yields stemming from the maintenance, storage and transfer of Mark 48 torpedoes. However, in general there are no records of the quantity of such activities and limited information on mishaps which lead to no explosive incident. There is also the problem that the activities or procedures may change slightly with changes in leadership at the facility. A third problem, of course, is the unknown deviations from standard operating procedures and equipment. The omission of these becomes part of the "error of omission" which frequently haunts the safety and hazard analysis.

*The tidewater hazard scenario refers to the ordnance operations performed within the confluence of piers, wharfs, and berthed ships at waterfronts where ordnance is received or offloaded for the purpose of homeporting. The type and number of ships, berthing arrangement of ships, quantity and type of ordnance aboard each ship, types of ordnance handling equipment, and nature of ordnance operations vary with time and geographical location. Each of these factors must be considered in estimating the sources, size and probability of accidental explosions. [Ref. 1]

USED MARK 48 TORPEDO (WAR SHOT)
SUBMARINE DOCKED ON NON-PIER SIDE OF TENDER SHIP

TORPEDO TRANSFERRED TO TENDER SHIP MONORAIL CRANE

1 RAISE, TRANSPORT ACROSS SHIP AND LOWER TO FLATBED TRUCK ON PIER

TRANSFER TO RACK ON FLATBED TRUCK

2 MOVE TO MK 48 TORPEDO SHOP (~3/4 MILE)

TRANSFER TO MOBILE CRANE

3 LOWER TO HANDLING CART

TRANSFER TO HANDLING CART

4 MOVE CART AND TORPEDO INSIDE BUILDING TO TEST AND MAINTENANCE BAY

TRANSFER TO BUILDING CRANE

5 LOWER TO HANDLING JIG IN TEST AND MAINTENANCE BAY

TRANSFER TO HANDLING JIG

6 REMOVE SENSOR, WARHEAD, AND GUIDANCE BAY

TRANSFER WARHEAD (VIA SLING) TO BUILDING CRANE (ALSO SENSOR AND GUIDANCE BAY IF NECESSARY)

7 MOVE WARHEAD, SENSOR AND GUIDANCE BAY TO BUILDING STORAGE RACK (OR FLOOR IF RACKS FULL)

TRANSFER WARHEAD ETC. TO STORAGE AREA

TRANSFER PROPELLANT TANK AND MOTOR TO BUILDING CRANE

8 BRING PROPELLANT TANK AND MOTOR TO CLEANING ROOM FOR CLEANING AND REFURBISHMENT

TRANSFER PROPELLANT TANK AND MOTOR TO CLEANING ROOM

9 CLEAN AND REFURBISH PROPELLANT TANK AND MOTOR

TRANSFER PROPELLANT TANK AND MOTOR TO BUILDING CRANE

10 BRING PROPELLANT TANK (AND MOTOR ASSEMBLY) TO REFUELING ROOM

TRANSFER PROPELLANT TANK (AND MOTOR ASSEMBLY) TO REFUELING ROOM

11 REFUEL PROPELLANT TANK

TRANSFER PROPELLANT TANK AND MOTOR ASSEMBLY TO CRANE

12 BRING PROPELLANT TANK AND MOTOR ASSEMBLY TO TEST AND MAINTENANCE BAY

TRANSFER PROPELLANT TANK AND MOTOR TO JIG IN BAY

TRANSFER WARHEAD (SENSOR AND GUIDANCE BAY) TO BUILDING CRANE

13 BRING WARHEAD (SENSOR AND GUIDANCE BAY) TO JIG IN TEST AND MAINTENANCE BAY

TRANSFER WARHEAD (SENSOR AND GUIDANCE BAY) TO JIG IN BAY

14 ELECTRICALLY MATE TORPEDO COMPONENTS THEN AUTOMATICALLY TEST. MECHANICALLY REASSEMBLE.

TRANSFER TORPEDO TO BUILDING CRANE

LOWER TO HANDLING CART

A

Figure 2-1. Ordnance Move/Store Operations (Mark 48)

A

TRANSFER TO HANDLING CART

16 MOVE CART AND TORPEDO OUTSIDE BUILDING

TRANSFER TORPEDO TO MOBILE CRANE

17 RAISE TORPEDO AND LOWER TO FLATBED TRUCK

TRANSER TORPEDO TO FLATBED TRUCK

18 BRING TORPEDO DOWN TO TENDER SHIP

TRANSFER TORPEDO TO TENDER SHIP MONORAIL CRANE

19 RAISE TORPEDO, TRANSPORT ACROSS SHIP AND LOWER TO SUBMARINE

B IS FOR VERTICALLY LOADED TORPEDOS ON SUBMARINES WITHOUT HYDRAULIC CHUTE

C IS FOR ANGLE LOADED TORPEDOS ON SUBMARINES WITH HYDRAULIC CHUTE

OFFLOADING PROCEDURE IS REVERSE OF B OR C

B VERTICALLY LOADED TORPEDOS

19 TORPEDO MANHANDLED TAIL FIRST DOWN THROUGH 23 INCH HATCH IN TOP OF SUBMARINE TO DOLLY CART IN SUB FLOOR

TORPEDO TRANSFERRED TO CART

20 CART PUSHED ALONG FLOOR OF SUB TO TORPEDO ROOM

TRANSFER TORPEDO TO CHAIN HOIST AND SLING

21 LIFT TORPEDO TO SUB MAGAZINE RACKS

TRANSFER TORPEDO TO MAGAZINE RACK

C ANGLE LOADED TORPEDOES

TORPEDO TRANSFERRED TO HYDRAUICALLY DRIVEN CRADLE AND CLAMPED

20 SLIDE TORPEDO INTO SUBMARINE TO CART ON MAGAZINE FLOOR WHICH MATES WITH HYDRAULIC SLIDE UNIT

TRANSFER TORPEDO TO CART

21 CART PUSHED ALONG FLOOR OF SUB TO TORPEDO ROOM (AS FOR VERTICAL LOADER)

TRANSFER TORPEDO TO CHAIN BOIST AND SLING

22 LIFT TORPEDO TO SUB MAGAZINE RACKS

TRANSFER TORPEDO TO MAGAZINE RACKS

OFFLOADING PROCEDURE REVERSE OF B OR C AS APPROPRIATE B AND C PROCEDURES ARE SAME FOR ALL CLASSES OF TORPEDO AND SUBROC MISSILE

Figure 2-1. Ordnance Move/Store Operations (Mark 48) (cont.)

Another set of activities for the move and store operations is shown in Figure 2-2. In this case torpedoes are brought to the tender from a vessel or barge and loaded directly into the tender on the side opposite the pier.

Mishaps in the handling of ordnance do not necessarily lead to a detonation. Much of the ordnance-handling activity, and the ordnance itself, is designed such that if a mishap occurs, such as the dropping of a warhead, the impact of the warhead on the surface will not create enough concussion within the explosive to cause a detonation. Many of the more modern and sophisticated explosives are also becoming more and more insensitive to shock of this nature. However, even though an explosive is reasonably insensitive to the shock from impact, there is a larger than zero probability that some form of detonation can occur. Hence, it will be necessary in treating risk during these handling activities to have conditional probabilities of explosion as a function of the nature of the mishap and the explosive. This will account for the fact that the drop of a warhead one foot off the ground will have a different probability of detonation than a drop from forty feet above the ground.

Also, the yield which may result from detonation may vary with the type of mishap that may occur. In general in this study, some small yields may not be of importance because their contribution to the expected damage or life loss may be small. Hence, yields smaller than a specified level will be ignored except where they present a fragment/debris hazard or can cause initiation of other explosives leading to events having very much higher yields. The problem of sympathetic detonation, therefore, becomes a critical element in the analysis.

Last, but certainly not least, in the consideration of the initiation of explosives, are the problems created by fire. The event sequences shown in Figures 2-1 and 2-2 are generally related to the dropping of ordnance. Fires are not always so easy to define from the standpoint of event sequences, and frequently, in the case of ordnance, may involve ordnance which is not in the handling process. Nevertheless, fires must be treated because of their very large potential to cause an ordnance explosion incident. Fires may also be the link which leads to a sequence of explosions resulting from an initial explosion. The approach to fire must be based on the occurrence of fire in all of the ordinary operations at a base. The initiation of explosives becomes a problem when fire, radiation, or heated air raise the temperature of the explosive to a point of instability.

NEW MARK 14 AND MARK 37 TORPEDO

SIDE LOADING ONTO TENDER SHIP

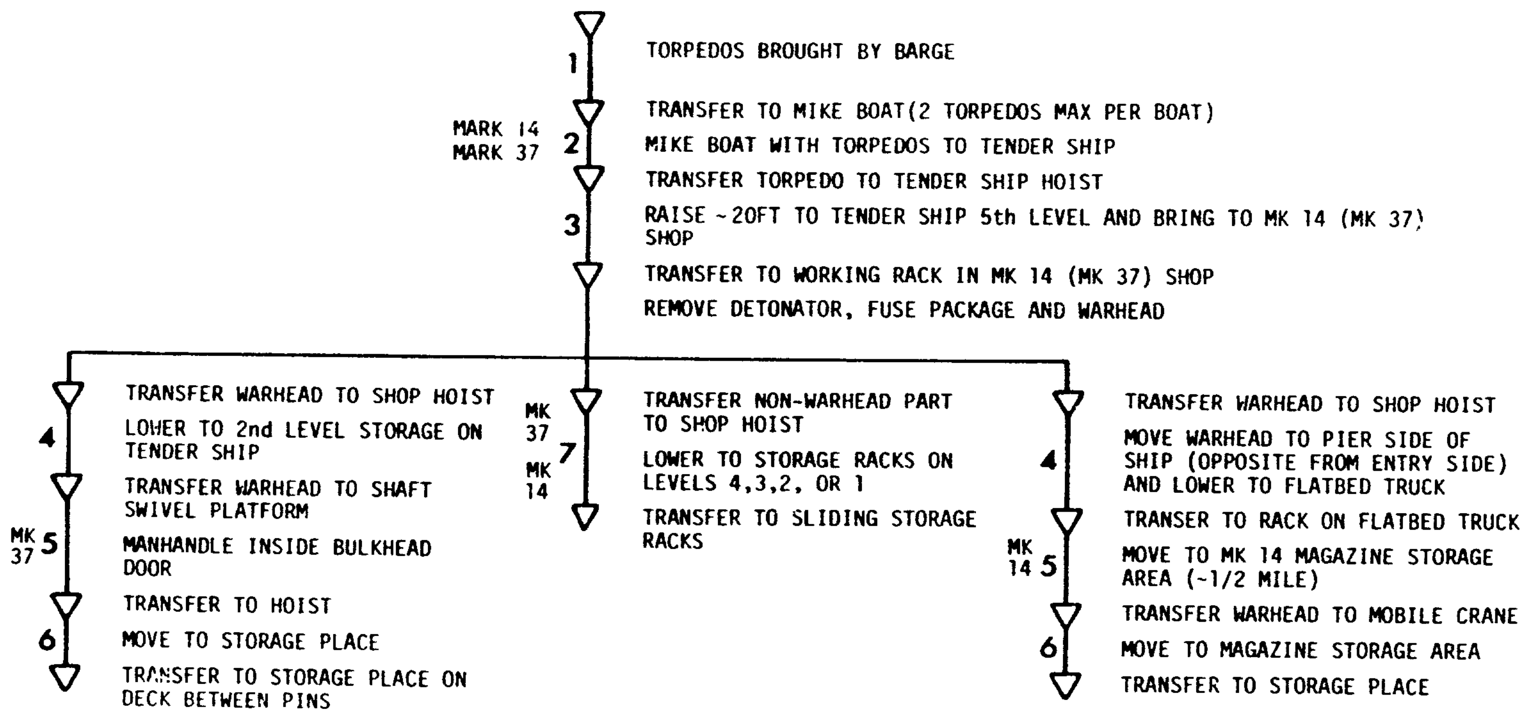

Figure 2-2. Ordnance Move/Store Operations (Mark 14, Mark 37)

3. SELECTION OF A METHODOLOGY

3.1 Goals, Objectives and Constraints

The goal of the Navy Explosives Safety Facilities (NESF) project is to develop an operational risk-decision model which will quantify the magnitude and identify the sources of risk and evaluate alternative policies (within specified operational, safety and budget constraints) for mitigating the risk to people and property from explosives hazards at the Naval Shore Establishment. A vital product element necessary to achieve the NESF goal is the characterization of Navy hazard scenarios, especially estimating the event (explosion) probability of each potential explosion source. In order to develop a sound technical approach, information is needed on the state-of-the-art techniques, new technology requirements, and anticipated risks in the goal to quantify the event (explosion) probabilities for Navy tidewater explosion hazard scenarios.

The problem that is being addressed in this particular study is that of establishing the probability of explosive events of various yields. The data base shows that accidental explosions are very rare events. The problem, then, is to develop a methodology which makes maximum use of mishap data, is reasonable in its predictions, and does not put undue requirements on data gathering within the Navy. Believability, of course, is a major problem, and the methodology must survive the critical challenge of the technical community.

The problem of an insufficient data base, either of operating procedures, mishaps, transactions, or accidental explosions, in general, prevents us from going to a traditionally deductive analysis at the detail (link) level. We must use either very general interpretations of past experience, or introduce inductive analysis with models and probability predictions in order to accomplish our goals. (Deductive analysis can be interpreted as those instances wherein the data base is of sufficient size that binomial statistics can be created for predicted mishaps with high confidence. If the Navy were to record all of its operations, and continue using precisely the same activity descriptions for a long period (50 years?), such a data base would be possible.)

3.2 Tradeoffs and Justification of Approach

The basic question in the selection of an approach is what is an appropriate level of detail? As the detail increases, costs of data development and program development increase. There is also the conceivable loss of credibility because the sum of the risk from a detailed description of a base may not equal the experienced overall risk at the base or similar bases. This happens because detailed methodologies (fault tree, etc.) are rarely able to model a priori all of the accident events that are experienced.

The most redeeming feature of a detailed approach is that it attempts to accurately locate and assign risk (yield and probability of yield) at all the points of possible accident events and it can be responsive to the characteristics of a particular naval facility. This detail then allows a more accurate assessment of the individual blast source/structural damage relationships when evaluating a facility. If the facility damage prediction (allocated by structure and personnel locations) does not need the detailed source data, then the detailed approach is not justified.

The other extremum of treatment of event probabilities is the employment of a gross summary of historical events at Navy facilities over the last 20-50 years to establish deductively the probability of occurrence of explosions. These probabilities would then be assigned to events occurring at each explosive storage or handling point. The yields associated with the events would be related to the weight of the stored explosive material at that location. The advantage of this approach is that the average numbers are easily justified by historical experience and the methodology is simple. The methodology accuracy is directly dependent upon the ability to identify all accident sources and to assign probabilities to the sources.

As the effort toward accurate assignment increases, the methodology moves in the direction of the detailed approach. The methodology is relatively insensitive to historical changes in procedures, explosive behavior, fire control and other influences on event probabilities. It is also limited in providing very accurate discrimination between the risk at the various bases.

The method that is proposed in this report falls in the category of the detailed approach. The detail shown may prove to be too fine, and it may be necessary to back off and use more general categories for link definitions and the accumulation of data. If the detailed method is adopted it should also be tested against the more deductive approach to assure a comparable level of total risk. The level of detail should reflect the needs of the risk analysis and the availability of resources to develop the data. Thus if the detailed approach can reflect a varying level of aggregation it can adjust more readily to the program requirements. Also, because of the evaluation of activities, paths, etc., more information can be made available about making changes in ordnance handling procedures and other activities related to risk.

In conclusion, it is suggested that an approach be adopted which provides as much detail as required to perform an accurate risk analysis. We suggest the approach be based on detailing activities and exposures and the corresponding development of appropriate data bases. To check the results we propose the use of historical data to test occurrence probabilities and yields.

4. PROPOSED METHODOLOGY

4.1 Introduction

The proposed methodology to be used for determining the probability of damaging explosions is summarized in Figure 4-1. This figure depicts the activities of a computer program, including the input and the use of three data bases. It is assumed that all explosions are the result of impact or fire related initiating events. The methodology assumes a detailed evaluation of activities which could lead to impact, a detailed evaluation of structures and activities which could lead to fire, and an iterated evaluation of secondary detonations due to the influence of neighboring explosions or fires.

The proposed methodology to be used for determining the probability of explosions of various yields is summarized in Figure 4-1. This figure depicts the activities of a computer program, including the input and the use there is always the chance of unknown and undefined events which could lead to disaster. To anticipate this, careful review should be made of the modeling process to make sure that there is adequate conservatism in the description and locations of all possible initiating events. Since the methodology described herein does not complete the risk model, but only supplies probabilities, it should be advised that the risk model in its formulation should anticipate this problem. One way that this problem can be minimized is to avoid the use of absolute risk, and concentrate on relative risk as it applies to the locating and use of structures at the tidewater.

The procedure as shown in Figure 4-1 will lead to the listing of probabilities of detonations at various locations and at various yield levels. The program will be structured to eliminate yields below a level producing little damage.

4.2 Facility Specific Input Data

Early in the project, a dictionary of specific activity definitions, structure classification, explosive types, etc., will have to be developed which will provide a basis for storage of data on mishap probabilities in the data bases. Then, all data developed for a particular facility will be developed in a format which is consistent with the data bases. The specific data preparation activities can be defined as follows:

(1) Structure activities and links from catalogue of activity links (define for Impact Events Data Base).

(2) Define locations, distances (if appropriate), durations and repetitions of all activities.

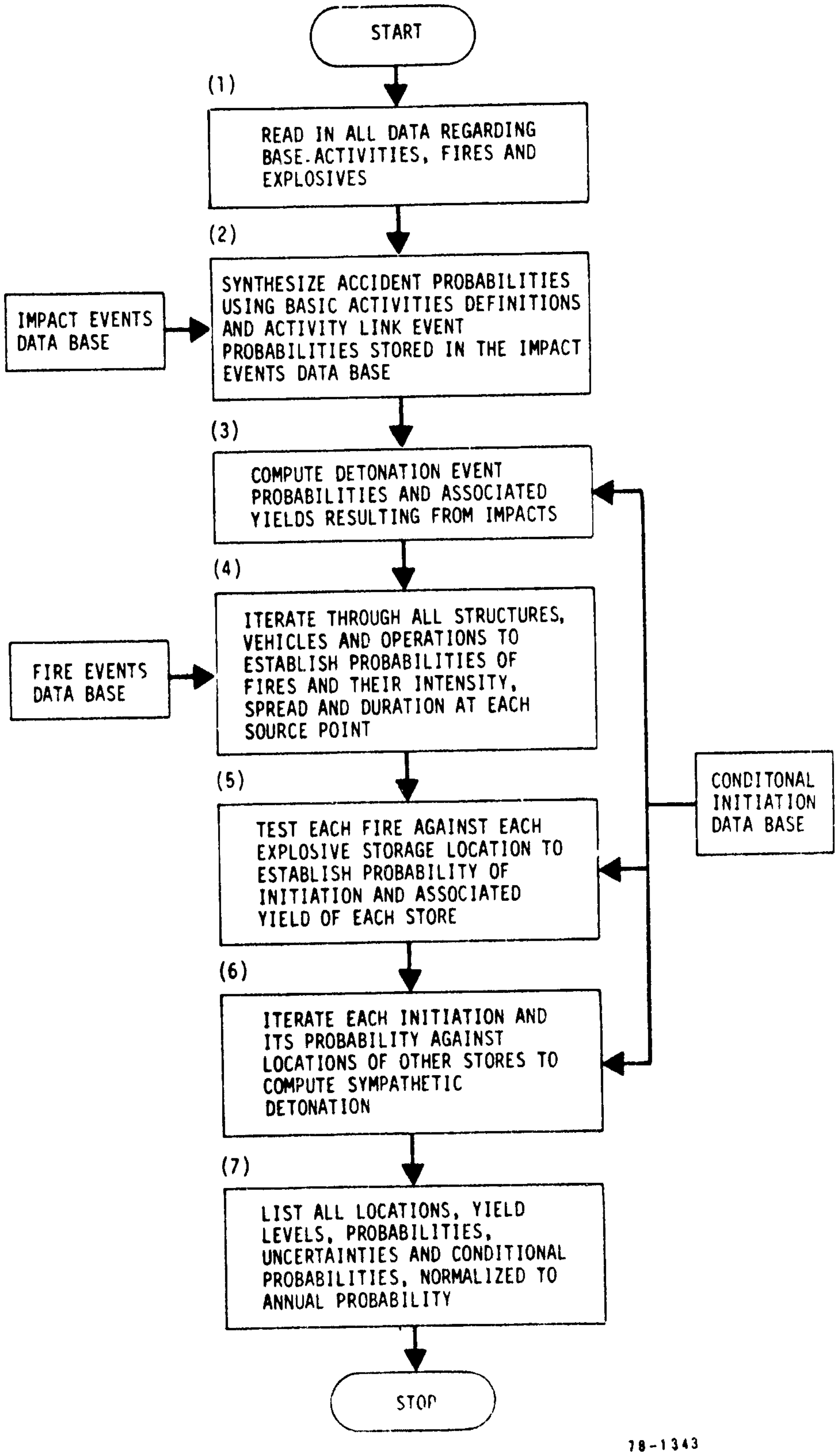

Figure 4-1. Proposed Methodology

(3) Define structure types, uses and fire controls using definitions consistent with the Fire Events Data Base

(4) Define yields of explosives, types of explosives and locations of explosives (definitions consistent with Conditional Initiation Data Base)

In preparing the data input for the computer, all of the data gathered described above would be key punched along with specific constraint data such as the lowest level of yield which is of interest in the problem, etc.

4.3 The Data Bases

It is proposed that three separate data bases be developed to contain the basic information with regard to event probabilities and conditional probabilities of detonation. The three data bases would be entitled "Impact Events Data Base," "Fire Events Data Base," and "Conditional Initiation Data Base."

4.3.1 Impact Events Data Base

The Impact Events Data Base would be constructed from experience within the Navy in the handling and transport of ordnance. Currently, at the Naval Surface Weapons Center, there is a complete reporting of all accidents with explosives. From this information, it will be possible to separate out those accidents which are impact-related. It may not be, however, easy to determine all mishaps which occurred which could have led to explosion from impact. In addition, there is currently no data base which numbers all of the activities in which an impact mishap could have occurred. When using binomial probabilities, the estimate of the true frequency of mishap (π) is estimated by the ratio r/n. Currently, r is available for reported accidents and n has not been recorded. Consequently, a methodology will have to be developed to establish n.

Since it has been proposed to break up the activities into basic links, it will be necessary to accumulate the data on r and n for each of these links. To do this, the Navy will have to go to the records for the transferral of ordnance and infer the number of transactions from the weight of explosive recorded in the records of hazardous material movements. Part of this information can be obtained from CAIMS (Conventional Ammunition Inventory Management System) which has records of all ordnance transactions. There is also an accounting of total weights of ordnance by the SPCC (Ships Parts Control Center). It may also be necessary to obtain individual records of ordnance movement at the base, but it will be important not to place upon Navy personnel any additional data reporting than is already required.

The development of the data base for impact events is summarized in Figure 4-2. The data base will need an addressing procedure so that activity links can be easily accessed and identified. In addition to the event probability data (r and n), other information should be stored, detailing such parameters as drop height, so that probability of detonation as a function of severity of a fall can be computed in a later step in the program. Also because the data base will be limited, parameters describing the prior estimate of the event probabilities will be included to afford Bayesian estimates of mishap probabilities.

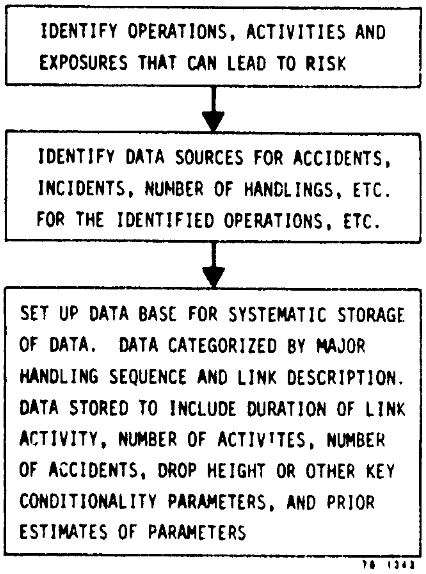

Figure 4-2. Data Base Development for Impact Events

4.3.2 Fire Events Data Base

The data base (Figure 4-3) for fire events will be constructed primarily from information gathered at the Navy Safety Center. A discussion of the structure of this data is described in the discussion of computing fire events. In addition, Appendix B contains tables which were used in the development of fire frequency probabilities in a previous study for NAVFAC [3]. The data base for fire frequency should prove reasonably straightforward to develop. Problems are going to start, however, when estimates must be made on the spread, intensity, and duration of fires as a function of fire load (stored flammable materials), efficiency of firefighting, effectiveness of fire control systems (i.e., sprinklers) and structural considerations. As discussed later, this area will contain considerable uncertainty.

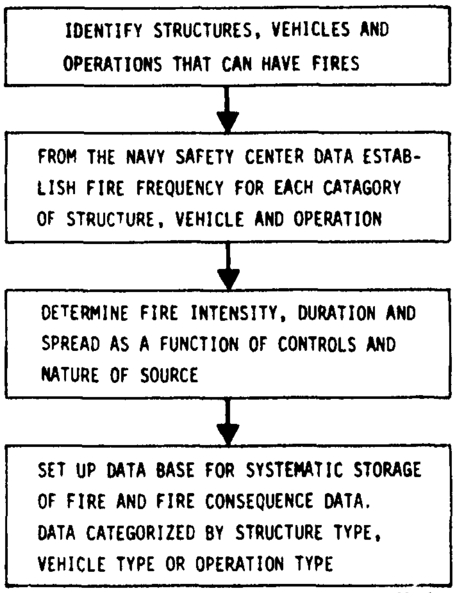

Figure 4-3. Data Base Development for Fire Events

4.3.3 Conditional Initiation Data Base

This data base (Figure 4-4) is to provide information on the probability of initiations of various ordnance based on velocity of impact, temperature and duration of temperature, effects of missile impacts, effects of overpressure, etc. Much of the information will be required in the form of conditional probabilities, e.g., the probability of a detonation given a fall of "x" ft. It is realized that there will be a sparsity of data in a number of areas involving a number of different explosive types. On the other hand, this conditional information is very important because, as ordnance changes, these conditional probabilities change, leading possibly to some rather large changes in the probability of certain explosive events. With the large uncertainties that can be anticipated in these probabilities or probability distributions, it will be expected that all numbers coming from this data base will be qualified by uncertainty distributions.

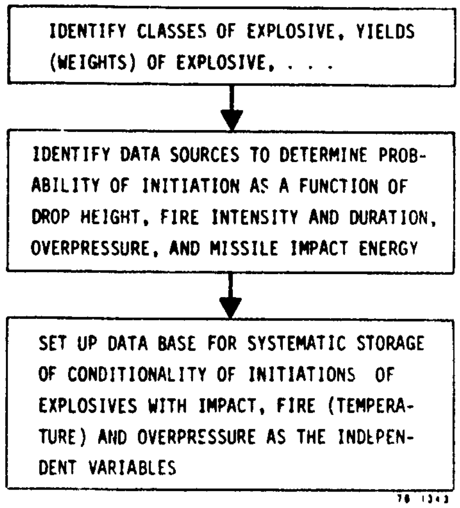

Figure 4-4. Data Base Develooment for Conditional Initiation

4.4 Impact Events

Explosions of ordnance due to impact either from falls or from impacting debris, could be considered as occurring at a frequency described by a Poisson process. This would lead to an exponential description of the probability of failure based on period of exposure to the particular accident environment. However, in this study, the proposed approach of breaking activities down into links, each having a mishap probability, eliminates the use of probabilities based on period of exposure. There may be exceptional occasions, such as transportation of explosives, where the travel distance can be broken into several links and thus the probability of mishap during travel can be proportionally increased with distance by adding links. This would be roughly equivalent to increasing the time of exposure and hence, the mishap probability.

Accident probabilities involving impacts as initiating events will be based on the following procedure:

(1) Each of the handling activities at the base will be broken into activity links which have descriptions in the impact events data base. Thus, the analyst who constructs the activity networks for ordnance handling, will have to make up these networks from defined links which have been included in the data base, and which have established probability distributions.

(2) Along with these defined activities, the user will have to input the location whereat the accidents can take place. Thus, the event can have a location as well as a probability.

(3) The probabilities will now be combined using the individual probabilities of the mishaps in the links to determine the probability of an event from an activity. It will be assumed that if an activity covers a wide area, such as transporting of ordnance, that it will be broken into several links, each having a representative location where the potential detonation could take place.

The probability of an event in one of the activity links will be represented binomially with its uncertainties described by a beta distribution. Since there is likely to be a sparsity of data. it is suggested that these binomial probabilities be developed using a Bayesian methodology which uses beta distributions as prior distributions. A discussion of this methodology follows in Section 5 and in Appendix A.

4.5 Computation of Detonation Events

The probabilities computed for impact events will provide the probability of mishap, but not necessarily of detonation. Accompanying the mishap probability will be the parameter upon which the conditional detonation probability is based. Thus, if a torpedo is dropped from 40 ft., the conditional detonation probability will be computed based on a fall of 40 ft. This probability will then be multiplied times the mishap probability to get the probability of detonation. Yield will also be included at this point to be carried forward in the analysis. Note that if the drop height of the torpedo warhead is two feet instead of forty, the conditional probability of detonation will be much lower as reflected by the information coming from the conditional initiation data base. It might also be mentioned here that the data base will have to contain drop heights and initiation information for all types of explosive materials and containments.

4.6 Fire Initiation of Explosives

The potential fires will be identified at particular locations at the facility. Each fire will have an intensity, duration, and probability. In the next computation, the ordnance locations will be compared to the fire locations and, using conditional probabilities of ordnance initiation based on the fire parameters and the proximity to the fires, probabilities of detonation of the various ordnance will be computed. The output of this computation would then be the yield and probability of detonation of the various ordnance due to fire.

4.7 Sympathetic Detonation

In previous steps in the program, individual detonations were computed and predicted due to causes by direct impact or fire. In many cases, this single initial event will not offer a threat to structures. However, if ordnance which does detonate is located closely to other ordnance, its initiation could lead to a much larger detonation by the communication from one weapon to another. Hence, the purpose of this step in the computation is to determine the likelihood of a larger explosion because of the initiation of ordnance at specific locations. This particular computation in the program would again depend on conditional probabilities obtained from the conditional initiation data base. It would require an evaluation of each ordnance location (and yield) relative to every other ordnance location (and yield). At the end of the computation, there would be a revision of the yields at each location and the probabilities that explosions could occur at these levels.

4.8 Output

The output of this proposed program is to be used as the input into a risk analysis. Required in the risk analysis is the location of each explosion, the yield at that location, and the probability that the explosion will take place on an annual basis. Hence the output of this routine will provide a list of all locations, yield levels (there may be more than one at each location) and the probabilities associated with each yield level. There will also be uncertainties associated with the probabilities. A discussion of how the density distribution of these uncertainties will be estimated is contained in Section 5.

5. STATISTICAL MODELS

5.1 Introduction

The purpose of this section is to describe in more detail the mathematical models which would be employed in the prediction of events due to impact, fire or sympathetic initiation. The approach to these models varies because of the varying structure of the problem and the varying quality of the data base. In each contributing part, uncertainty of the answer will be a real problem and thus an effort is made to synthesize these uncertainties and carry them forward along with the "best estimates" of each final explosion probability.

5.2 Mishap (Impact) Probability

As mentioned earlier, the use of links in the definition of activities permits the application of binomial probabilities in evaluating the occurrence of mishaps during these links. The product of mishap probability and the conditional probability of a detonation given the mishap will provide the probability of a detonation during a link activity

$$P_r(\text{detonation}) = P(\text{det}|\text{mishap})P(\text{mishap}) \tag{5-1}$$

P(mishap) will be binomial in form. P(det|mishap) will be dependent upon the nature of the mishap (e.g., the height of fall) and must be developed from theoretical and experimental data. Since P(det|mishap) is a function of an independent variable (such as height) there will quite likely be insufficient data to accurately define the relations and the uncertainty distributions will become the result of judgment by analysts. This will be discussed further in Section 5.4.

The problem that is posed by the mishap probability data is that it is probably too sparse to provide a confident estimate of the true probability of mishap, π. The maximum likelihood estimate of π is the ratio r/n. Event probabilities of 1×10^{-3} to 1×10^{-7} are expected and it is unlikely that the current data base will have a record of up to 10^7 activities (n) in order to have sufficient experience to provide an accurate estimate of π from r/n.

The classical statistical (deductive) approach to this problem relies entirely on the ratio of r/n. With π expected to be very, very small, it is very likely that the data base will provide r = 0 and n relatively small. The resulting confidence bounds on the estimate of π will probably be relatively wide and produce estimates of π which would give unacceptably high upper confidence bounds for the probability of occurrence of a mishap. These probabilities would be unacceptably high because intuitively the Navy experience over the past half century has not had a mishap rate as high as these bounds from a limited sample would indicate The problem is that the recorded sample size for well defined activities will be very small compared to the aggregation of activities over many, many years.

Having the statistical model rest entirely on carefully monitored experience is always preferred. And, as the data base grows over time it will become more adequate in providing the necessary information to properly estimate the values of π for each link. In the meantime, however, it is suggested that a Bayesian approach be used wherein the greater period of history of explosive handling be interpreted into a judgment of what the true mishap probability might be. This Bayesian approach balances judgment (prior) with data to provide a more balanced estimate (posterior). As the accuracy of the estimate of π increases with the expanding data base, the influence of the prior decreases until the posterior from the Bayesian approach is essentially equivalent to that which would result directly from the classical statistical approach. Thus, the purpose of the use of a Bayesian model is to insert judgment into the computation when the data base is inadequate. This judgment, in effect, artificially expands the data base, but its influence diminishes as the data base increases.

In the case of binomial sampling, a Beta distribution as typified in Figure 5-1 is mathematically very convenient in establishing the shape of the distribution for the prior estimate of π, and also represents the probability distribution of the posterior estimate of π. The mathematical development in Section A.1 of Appendix A demonstrates how the beta distribution can be derived from a conditional probability relation involving the binomial distribution.

The Beta distribution is continuous with the limits of 0 and 1 and has two parameters, n and r. The density function is shown in Equation 5-2.

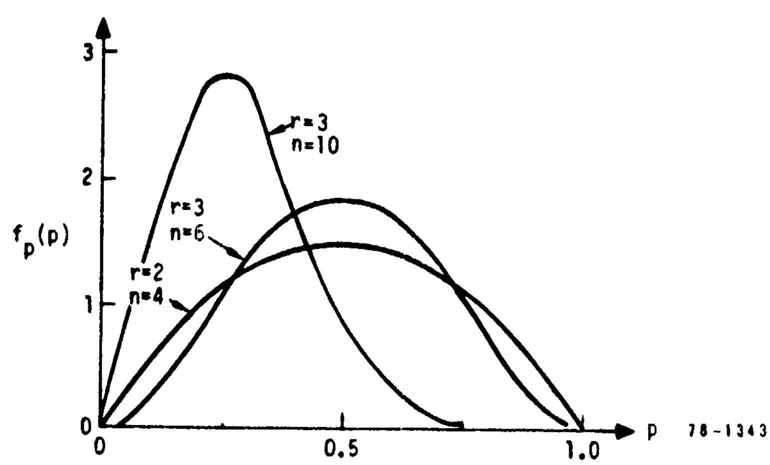

Figure 5-1. Beta Distribution Density Function

$$f_p(p) = \frac{1}{C} p^{r-1} (1 - p)^{n-r-1}, \quad 0 \leq p \leq 1 \tag{5-2}$$

$$= 0 \text{ elsewhere}$$

where

$$C = \frac{\Gamma(r)\Gamma(n - r)}{\Gamma(n)}$$

and $\Gamma(\ )$ is a Gamma function [4]. r and n-r must be positive, but need not be integers.

The mean and variance are

$$\mu_p = \frac{r}{n} \tag{5-3}$$

$$\sigma_p^2 = \frac{r(n - r)}{n^2(n + 1)} \tag{5-4}$$

If r and n are integers, the density function takes the form

$$f_p(p) = \frac{(n - 1)!}{(r - 1)!(n - r - 1)!} p^{r-1} (1 - p)^{n-r-1}, \quad 0 \leq p \leq 1 \tag{5-5}$$

$$= 0 \text{ elsewhere}$$

and the values of the beta density function can be determined from tables of the binomial distribution. This relationship with the binomial distribution is very convenient and, in fact, the beta distribution, in the lexicon of Bayesian statistics, is known as the "conjugate prior" [5,6,7] to the binomial distribution when using Bayes Theorem to make estimates of the distribution of the probability of an event.

If the parameters, r and n, of the beta distribution are not known, but the mean and variance are known, the parameters can be computed as follows:

$$n' = \frac{\mu_p(1 - \mu_p)}{\sigma_p^2} - 1 \tag{5-6}$$

$$r' = \mu_p \frac{\mu_p(1 - \mu_p)}{\sigma_p^2} - 1 \tag{5-7}$$

Thus if an individual has a judgment on what the values of μ_p and σ_p are, he can then construct an "equivalent" sample size, n', and number of incidents, r'. As will be shown in Appendix A, the combination of the prior (the "equivalent" n' and r') with actual sampling, produces a new beta distribution (posterior) having parameters

$$r'' = r' + r \tag{5-8}$$

$$n'' = n' + n \tag{5-9}$$

Note that when n and r (the actual data) become large in comparison to n' and r', the effect of the data completely overshadows the original estimate. On the other hand, when the data is sparse, the analyst's judgment which leads to r' and n' is very important.

The development in Appendix A demonstrates that regardless of whether a Bayesian approach is used or not, the beta distribution represents the uncertainty distribution for the binomial. Hence, in the final representation of uncertainty, the distribution as shown in Equation (5-2) is valid with either n and r or n" and r" as the parameters.

5.3 Fire Events Probabilities

The occurrence for fire may be considered a relatively rare and random event. Using a Poisson process to represent these events, the probability of occurrence of ν fires in time t is

$$P_f(\nu) = (\gamma_m t)^{\nu} \frac{e^{-\gamma_m t}}{\nu!} \tag{5-10}$$

where ν_m is the mean number of fires in the subject structure.

For buildings, Lie [8] and Burros [9] suggested that $\gamma_m = \rho A$ where A is the total floor area of the building and ρ is a constant representing buildings with similar occupancies. The expression is valid even if the building has unequally sized compartments.

In Ref [2], seven years of Naval on-shore fires data was obtained, translated into fire frequency and presented in tabular form. An abbreviated version of this information is shown in Table 5-1 [10]. The complete tables are reproduced from Ref [2] and included in Appendix B.

OCCUPANCY *	FIRE FREQUENCY ~ ρ
Cold storage and refrigeration bldg.; engine test cells, hangers; wharves	0.1 - 0.5 [.432]
Drydocks; R & D labs; schools and training bldg.; warehouses; misc. repair shops	0.5 - 1.0 [.649]
Manufacture, assembly, and modification bldg.; commissaries; retail stores; churches; child care centers; offices; family dwellings; garages; ordnance storage bldg; rec. bldg.	1.0 - 3.0 [2.11]
Communication and navigation bldg ; medical facilities, power, heat, and utility bldg.	3.0 - 5.0 [4.54]
Barracks, clubs, eating facilities; prisoner housing	5.0 - 10.0 [6.32]
Fire and police stations; banking facilities; museums; laundries and dry cleaning bldg.	10.0 - 50.0 [27.9]
Auto gas stations	>50.0 [73.5]

* Edited list. Mean value shown in brackets.
(1 fire per sq ft = 10.75 fire per m^2)

Table 5-1. Fire Frequency by Building Occupancy
(10^{-6} fires per year per square foot)

No corresponding data were acquired for vessels moored at piers in the harbor. Such information along with land vehicle data would have to be gathered to complete the data base. In addition, uncertainties in the values of ρ must be developed but these uncertainties cannot be developed around binomial sampling because even though the number of fires (r) is known, the number of opportunities (n) is not. The rate ρ was developed by dividing r by the total square footage of exposed buildings in the appropriate categories. The distribution can best be described by studying the year-to-year variation of r (normalized for the adjustments in total exposure each year). A superficial review of Table 1 in Appendix B indicates that the coefficient of variation ($s_r/\bar{r}$) for r is usually less than one and frequently less than one-half. This would indicate that the resulting distributions for ρ would have similar coefficients of variation. Assuming ρ to be log-normally distributed (no solid justification at this point), one will obtain uncertainty bounds having reasonable width.

Fire intensity and duration will be dependent upon the type and quantity of flammable material in the structure or vehicle, the building or vehicle construction, the level of fire protection (sprinklers, etc.) and the efficiency of the available firefighters. This information is not currently available and will have to be developed from studying the records of fires at the Navy Safety Center. Fire damage algorithms have been developed by Lee [2] for structures using a Delphi study involving Navy fire experts. The results of this study showed a wide spectrum of opinion as to degree of damage given a set of conditions. A typical set of fire damage matrices, from Ref [2] is shown in Table 5-2. Note that the numbers in each column are probabilities and sum to one, thus representing a probability density function of damage level.

BUILDINGS WITH NO FIRE PROTECTION OTHER THAN THAT INHERENT IN THEIR CONSTRUCTION																		
CONSTRUCTION TYPE	FIRE RESISTIVE						NON-COMBUSTIBLE						ORDINARY/WOOD FRAME					
INTERIOR FINISH	NON-COMBUSTIBLE			COMBUSTIBLE			NON-COMBUSTIBLE			COMBUSTIBLE			NON-COMBUSTIBLE			COMBUSTIBLE		
DAMAGE STATE (J) \ FIRE LOAD	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE
MINOR (1)	72	65	52	.58	52	46	70	61	48	53	42	36	52	41	31	31	23	20
LIGHT (2)	16	16	17	23	25	19	16	20	17	18	20	17	18	23	18	20	16	14
MODERATE (3)	08	13	.19	12	15	20	09	11	15	.13	19	25	.14	17	.19	19	27	24
HEAVY (4)	03	04	07	05	.05	08	03	04	09	08	09	.10	10	11	18	14	16	18
TOTAL (5)	01	02	05	02	03	07	02	04	11	08	10	12	06	08	14	16	18	24

Table 5-2. Typical Set of Fire Damage Matrices

For the problem being considered in this study, structure damage from fire is secondary to the areal extent, the intensity and the duration of the fire. It will be upon these parameters that probabilities of initiation of exposed ordnance will be based. Hence the additional effort with the Navy Safety Center data base will have to contain an evaluation which will aid in quantifying these parameters. Undoubtedly these parameters will have a significantly larger uncertainty than the fire frequency parameter, ρ.

5.4 Conditional Detonation Probabilities

It is assumed that the conditional probability of detonation will have a functional form of the nature shown in Figure 5-2.

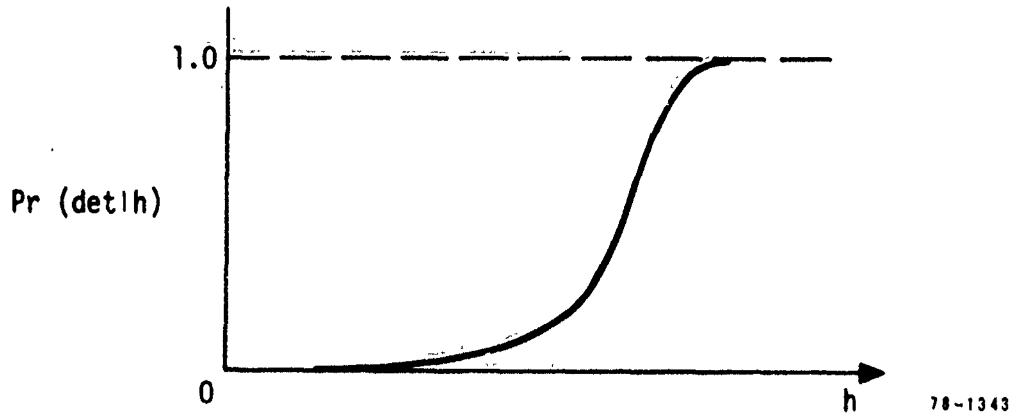

Figure 5-2. Conditional Probability of Detonation

The precise form of such a curve can only be determined after many tests made at varying values of h. Since the nature of the results would be interpreted as binary, a proper evaluation tool would probably be probit analysis [11]. Regardless, there would probably be a great deal of scatter and also partial detonations to confuse the precision of the conditional probability. Thus, along with the best estimate of Pr(det|h), a distribution of uncertainty will be required <u>for each value of h</u>. This distribution is typified in Figure 5-3.

It is probable that the uncertainties shown in Figure 5-3 are probably less than those which will result from a systematic study of the problem. The uncertainty is compounded by lack of test data, inability to scale data, and the variability of materials.

The uncertainty can probably best be modeled by the beta distribution because of the 0 to 1 limits of the distribution. The distribution parameters would be established using Equations (5-6) and (5-7). Whether a Bayesian approach with both judgment and data could be used is not certain. A test program of any real scale may be too expensive and, in this case, there may have to be very heavy reliance on the judgment of professionals in the field, supported by selective analyses and tests.

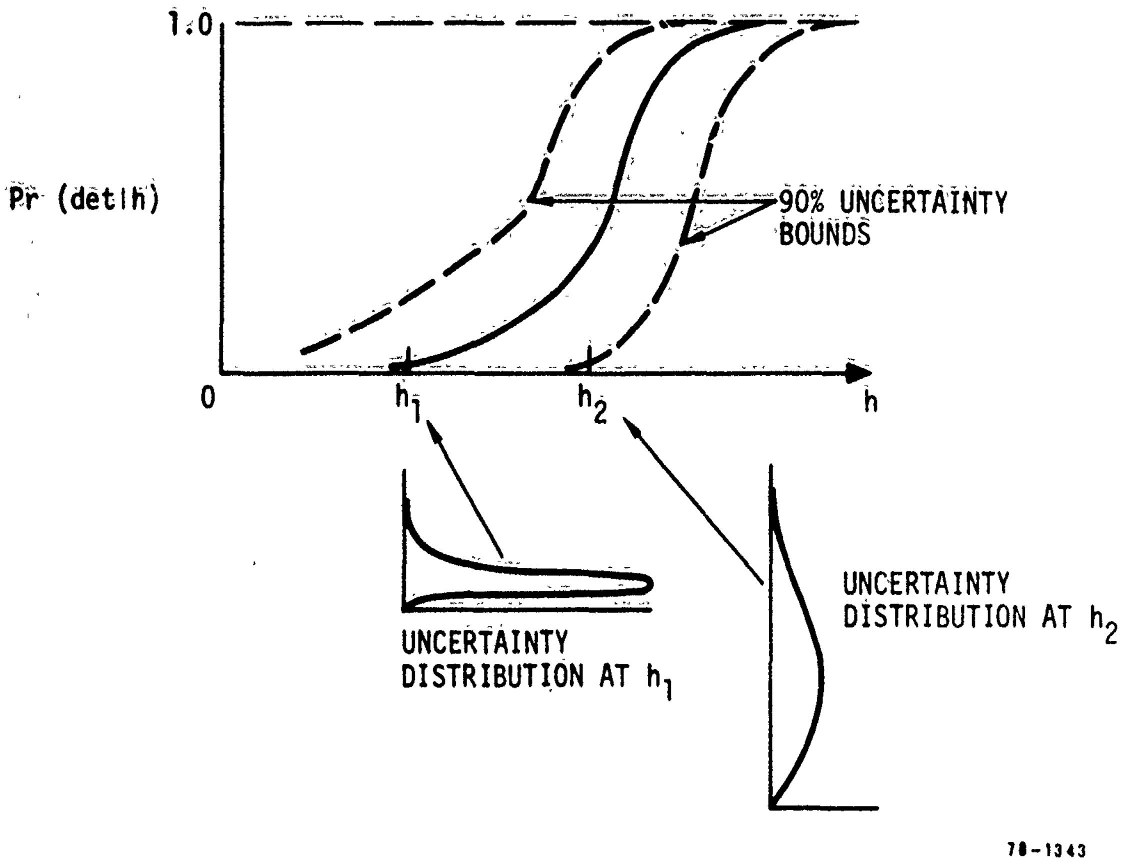

Figure 5-3. Uncertainty of Conditional Probability of Detonation

5.5 Synthesis of Probabilities

The final output of the analysis must be a list of events and locations of these events, and then a series of levels of yields with probabilities associated with each. The probabilities will be the result of a sum of independent mishaps located at the same place, multiplied by the conditional probabilities associated with the nature of the initiating event. The probability of a detonation of a particular yield at a particular location could be represented by the expression

$$Pr(Y_j) = \sum_{i=1}^{m} Pr(Y_j|h_i)\ Pr(E_i) \tag{5-11}$$

where $P(E_i)$ is the probability of mishap E_i which has a parameter h_i (such as drop height) and $Pr(Y_j|h_i)$ is the conditional probability of yield Y_j given parameter h_i. h_i could also refer to a collection of fire parameters or parameters associated with the environment created by the detonation of other ordnance.

It is probably desirable to deal only with preselected discrete yield levels in order to reduce the number of final computations. These levels must be close enough so that the incremental changes in levels will not be large enough to create errors in the eventual computation of expected damage in the risk program.

The biggest problem in the synthesis of probabilities will be with the propagation of uncertainty through the model. Since the probability uncertainties may be represented by various distributions (beta, log normal, etc.) and, because the probabilities appear both as products and sums, it is suggested that the uncertainty distributions on yield probability be determined by Monte Carlo simulation. There may be some difficulties with this because of the low probability of events and the resulting need for a very large number of cycles. Since the computations are rapid, the many cycles may not prove to be a problem, however, random number generation of beta variables could still be a problem (see Appendix A) and the lognormal distribution may prove to be the more desirable distribution. A flow diagram of a typical Monte Carlo routine is shown in Figure 5-4.

A second less precise but cheaper method to obtain the uncertainty in $Pr(Y_j)$ is to form a Taylor Series expansion of Equation (5-11). If all higher order terms are ignored, the expansion becomes

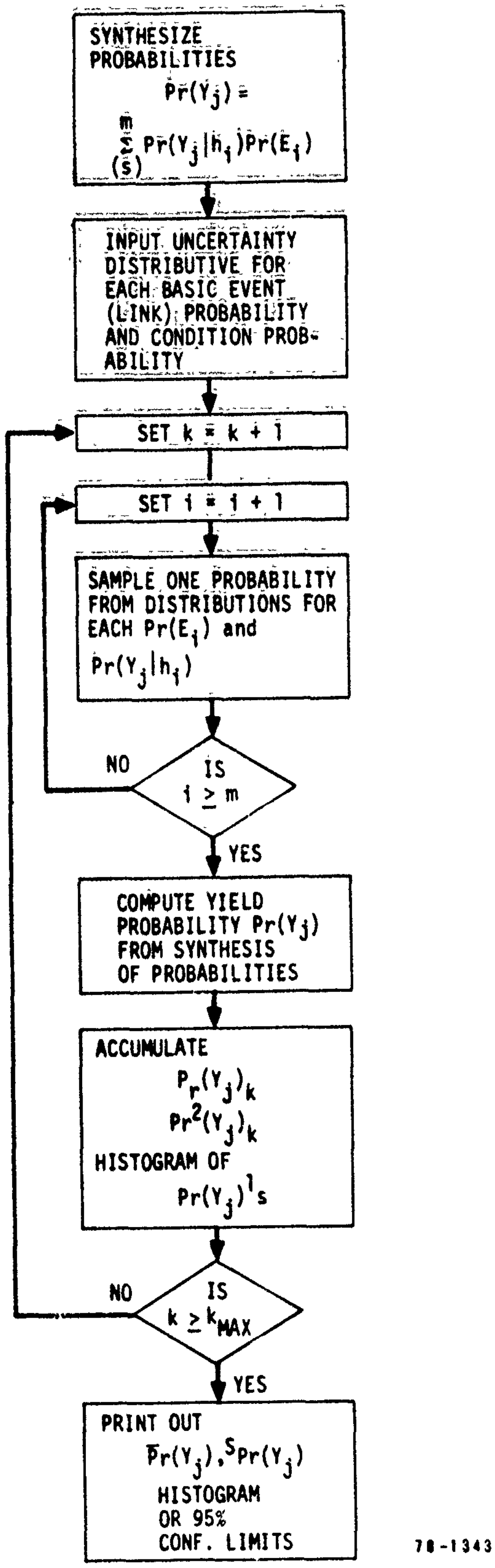

Figure 5-4. Monte Carlo Routine for Computing the Distribution of $Pr(Y_j)$

$$\Delta Pr(Y_j) \cong \sum_{i=1}^{m} Pr(Y_j|h_i)\ \Delta Pr(E_i) + \sum_{i=1}^{m} Pr(E_i)\ \Delta\, Pr(Y_j|h_i) \tag{5-12}$$

Then

$$\sigma^2_{Pr(Y_j)} \cong \sum_{i=1}^{m} Pr^2(Y_j|h_i)\ \sigma^2_{Pr(E_i)} + \sum_{i=1}^{m} Pr^2\ (E_i)\ \sigma^2_{Pr(Y_j|h_i)} \tag{5-13}$$

This assumes statistical independence of all $Pr(E_i)$ and $Pr(Y_j|h_i)$ which may not be true. It also provides only a variance and not a distribution. Nevertheless, it is probably worth further examination if the simulation approach appears to be too expensive.

6. DATA DEVELOPMENT

The methodology suggested in this report requires the development of three data bases which were discussed in Section 4.3. The message is clear that no systematic evaluation of risk due to explosive detonation can be performed without a well-defined and developed set of data bases. Thus, if this approach is adopted, a commitment must be made to formulate the procedures and definitions necessary to collect data in the format necessary to compute the mishap probabilities, conditional probabilities and fire probabilities. It is most likely that each data base would be a separate activity. The impact events data base would arise from a careful study of all of the different handling procedures for ordnance that are now in existence at the various Naval facilities. These studies would provide a basis for estimating the number of exposures (n) which can be coupled with the number of mishaps (r). The work would probably require developing methods to infer the number of activities in various links from reports of movement of ordnance which do not have the required detail. As emphasized earlier in the report, it will be necessary to devise study procedures that will not create new data handling problems for active Navy personnel at the facilities.

The fire events data base will require extensive interaction with fire prevention and control personnel within the Navy. It may also require searches within the literature to establish means to predict duration, intensity, and extent of fires.

The conditional initiation probabilities will require laboratory support. The numbers associated with these probabilities, as mentioned earlier, will probably result from the combination of test results and analysis. There will be a number of variables involved: conditional probability of initiation from impact; conditional probability of initiation from thermal environment; and conditional probability of initiation from the environment created by detonation of neighboring ordnance.

APPENDIX A

MATHEMATICAL DEVELOPMENTS

A.1 Computation of Mishap (Impact) Probability Using the Binomial and Beta Distributions

The purpose of this section is to define alternatives for characterizing mishap probability for each link. The objective is to define an estimation procedure which will allow maximal consistent use of existing data, facilitate the update of the estimates as new data become available, and provide a means of expressing the uncertainty in these estimates.

We adopt the perspective that each time a handling link is exercised (a given type of handling occurs) that a sample has been taken from an infinite population of all possible occurences of the link (under comparable conditions). Two types of descriptions are appropriate to this viewpoint: (1) We can regard each exercising of a link as a Bernoulli trial with the possible outcomes of a mishap and no mishap; and (2) We can describe the occurrences of mishaps as a time dependent Poisson process.

First consider the Bernoulli trial description. Bernoulli trials are characterized by the binomial distribution. If the per trial mishap probability is designated as π, then the probability of exactly r_0 mishaps in n trials, Pr $(r = r_0)$, is given by

$$\Pr(r = r_0) = \binom{n}{r_0} \pi^{r_0} (1-\pi)^{n-r_0} \tag{A-1}$$

The probability of r_0 or fewer mishaps in the n trials, Pr $(r \leq r_0)$ is calculated to be

$$\Pr(r \leq r_0) = \sum_{k=0}^{r_0} \binom{n}{k} \pi^k (1-\pi)^{n-k} \tag{A-2}$$

In the problem at hand, having observed the number of mishaps, r, and the number of trials, n, we wish to estimate π by a number p based on the data. A natural requirement is that the estimate be one that is best supported by the data. The maximum likelihood estimator fulfills this requirement as well as having other desirable statistical properties. The maximum likelihood estimator, p, for π is given by

$$p = \frac{r}{n} \tag{A-3}$$

In estimating mishap probability it should be noted that while the anticipated sample sizes (n) are moderately large (10^3 - 10^6), the anticipated number of mishaps (r) is small (0 - 10). In particular, it is likely that for many operational links the historical records will show no mishaps. While it is reasonable to say that this indicates that the true mishap probability is very small, it is altogether inappropriate to blindly apply the maximum likelihood estimator and estimate $\pi = p = \frac{0}{n} = 0$. Instead, we inquire what probability distribution function for p the data supports.

Absent of any data or knowledge of the likely value for π, the mishap probability, it would be reasonable to say that all values, $0 \leq p \leq 1$, are equally likely. For any fixed value of p the probability of exactly r_0 mishaps in n trials, $Pr(r = r_0 n|p)$, is given by Equation (A-1). Applying the multiplicative law for conditional probability and the assumption that all values of p were equally likely (p is uniformly distributed), we calculate the absolute probability of r_0 mishaps as follows:

$$Pr\ (r = r_0) = \int_0^1 Pr(r=r_0,n|p)Pr(p)dp$$

$$= \int_0^1 \binom{n}{r_0} p^{r_0}\ (1-p)^{(n-r_0)} \cdot 1\ dp$$

$$= \frac{n!}{r_0!(n-r_0)!} \frac{r_0!(n - r_0)!}{(n + 1)!} = \frac{1}{n + 1} \tag{A-4}$$

Now, with the information that r_0 mishaps were observed in n trials we can apply Bayes' theorem to determine the distribution of p that this implies. Bayes' theorem for probability density functions states

$$h(p''|r) = \frac{f(r|p')g(p')}{f_r(r)} = \frac{f(r|p')g(p')}{\int f(r|p')g(p')dp'}^{*} \qquad (A-5)$$

The density function for p" given r (the posterior density) is equal to the product of the density function for r given p' and the absolute probability density function for p'(the prior density) divided by the absolute density function for r. This result may be derived by successive applications of the multiplicative law for probabilities. Thus, the density function for p" after r mishaps in n trials is given by

$$\begin{aligned} h(p''|r = r_0) &= \frac{1 \cdot Pr(r=r_0,n|p')}{Pr(r=r_0|n)} \\ &= \binom{n}{r_0}(n + 1)p''^{r_0} (1 - p'')^{(n-r_0)} \qquad (A-6) \\ &\frac{\Gamma(r_0 + 1)\Gamma(n - r_0 + 1)p''^{r_0} (1 - p'')^{(n - r_0)}}{\Gamma (n + 2)} \end{aligned}$$

---

* This is derived from the multiplication law of probability where $Pr(A \cap B)=P(A|B)P(B)=P(B|A)P(A)$ which when rearranged gives $P(A|B)=\frac{P(B|A)P(A)}{P(B)}$. The probability density form of this equation is given above in Equation (A-5). The Bayesian formulation can be interpreted as finding a new value of the probability of A due to the occurrence of B. P(A) is defined as the prior (original) estimate of the probability of A and P(A|B) is the revised (posterior) estimate. The ration P(B|A)/P(B) is the "likelihood" that the result B would occur given the prior P(A). Developments and discussions of the Bayesian methodology are included in a number of texts [1,2,3].

This probability density function (p.d.f.) as mentioned in Section 5 is known as the beta p.d.f. In subsequent discussion we will use the shorthand $1/B(r_0, n-r_0)$ for the coefficient appearing in this p.d.f.

Suppose that all of the data collected up to some designated time have resulted in r mishaps out of n handlings. Suppose that in the next increment of time, r' mishaps occur in n' handlings. Then, by Equation (A-6) the p.d.f. for p" with these data is given by

$$h(p''|r'' = r+r', n'' = n + n') = \frac{p''^{(r+r')} \ (1-p'')^{(n+n'-r'r')}}{B(r+r', \ n+n'-r-r')} \tag{A-7}$$

Consider the same data from a different perspective: After collecting the first sample our best estimate of the distribution of p is given by

$$h(p''|r'' = r, n'' = n) = \frac{p''^{r} \ (1-p'')^{(n-r)}}{B(r, n - r)} \tag{A-8}$$

We wish to employ Bayes' theorem Equation (A-5) using Equation (A-8) as a prior together with the r' mishaps out of n' handlings in the second epoch. The new density is given by

$$k(p'''|r, r', n, n') = \frac{h(p''|r, n) \ f(r''|p', r, n, n')}{\int h(p|r, n) \ f(r''|p, r, n, n') \ dp} \tag{A-9}$$

The denominator is calculated as follows:

$$I = \int_0^1 \frac{p^r(1-p)^{n-r}}{B(r, n-r)} \binom{n'}{r'} p^{r'}(1-p)^{n'-r'}\, dp$$

$$= \frac{\binom{n'}{r'}}{B(r, n-r)} \int_0^1 p^{r+r'}(1-p)^{n+n'-r-r'}\, dp$$

$$= \frac{n'!(n-r)!\, r!\, (r+r')!\, (n+n'-r-r')!}{n!(n'-r')!\, r'!\, (n+n'+1)!} \qquad \text{(A-10)}$$

The numerator is given by the integrand of Equation (A-10). Thus, the new posterior is their ratio:

$$k\,(p''' \mid r, r', n, n') = \frac{p'''^{\,r+r'}\,(1-p''')^{n+n'-r-r'}}{B(r+r', n+n'-r-r')} \qquad \text{(A-11)}$$

This is the same result we obtained treating the data as a single batch. In other words, as we might expect, the Bayesian calculation is consistent, when applied as described above, with a direct calculation of the distribution of p.

Let us vary the above procedure: Suppose that in the first time period our record keeping was incomplete. It might, for example, be that data would indicate only that over a given time period (of known activity level) the total number of mishaps. For example, between World War II and 1960 it is possible that detailed records are unavailable. It would be more likely to discover written records of major accidents and only personal recollections of, say, the number of times torpedos were dropped To use this information we must distribute these mishaps to links and assess link activity. This information may be characterized using estimates of "pseudomishaps" that occur during the "pseudotrials" in which the link is exercised, or it may be characterized in terms of an estimate of mishap probability and the uncertainty of this estimate. In the former case, the number of "pseudomishaps" is used as r_1, and the number of "pseudotrials" is used as n, in equation (A-11). In the latter case, we use the relationship between the beta parameters r and n and the expected posterior mishap probability, E[p"], and its variance Var[p"]:

$$E[p''] = \frac{r + 1}{n + 2}$$

where in this case the original assumption of a prior with uniform distribution produces r' = 1 and n' = 2 and p" is the posterior estimate of π

$$Var[p''] = \frac{(r + 1)\ (n - r + 1)}{(n + 2)^2\ (n + 3)} \qquad \text{(A-12)}$$

Care should be taken in exercising this approach, as the very versatility of the beta distribution leads to undesirable results from certain combinations of means and variances. Values of r less than one result in a U shaped distribution. This results in an unreasonable distribution for many cases when combined with data from a new epoch. If, for example, in the new epoch no mishaps have ocurred, the Bayesian procedure results in a "choice" of the left arm of the distribution resulting in a disproportionate variance reduction. As a traceable data base develops, mishap probability estimates from the Bayesian type of analysis are governed increasingly by the data.

In addition to the care required in selecting values for the prior distribution with the beta distribution, there are in the present context special problems in generating random numbers with this p.d.f. The usual technique of generating a beta variate is to generate two gamma variates from products of uniform random variables and the beta distributed random variable from the gamma variates. This is hopelessly unwieldy for the size of n (number of times a link is exercised) expected. The other standard method involves the use of the cumulative beta distribution function. While it might appear that the simplicity of the beta distribution would make a closed form implementation of this straightforward, the large values of n make this approach numerically intractable. On the other hand, percentage points on the beta distribution can be built up either directly using a numerical quadrature technique (e.g., Gaussian quadrature), or if the exact percentag points where the distribution is known is considered important, using a root finder (e.g., Newton-Raphson) in conjunction with numerical quadrature.

When adequate data are available for characterizing mishap probability for each link, an asymptotic relationship allows us to employ the χ^2 distribution which is more conducive to generating random numbers. Define Λ as the likelihood ratio

$$\Lambda = \frac{p^r(1 - p)^{n - r}}{(r/n)^r(1 - r/n)^{n - r}} \tag{A-13}$$

Then $-2(\ln \Lambda)$ is asymptotically chi square distributed with one degree-of-freedom. Thus, to generate a random sample one could sample from χ^2 with one degree of freedom to compute $-2\ (\ln \Lambda)$, and solve Equation (A-13) for p.

A.2 Computation of Mishap Probabilities Using the Log Normal Distribution

An alternative approach for the Bayesian analysis is the use of a log normal distribution for mishap probability. This approach has the distinct advantages of resulting in a distribution of a reasonable form for all data cases that might be expected, being more amenable to the form in which the initial mishap probability distribution is likely to be available, and being an easy distribution for generating random numbers. Past experience has shown that the initial estimates are likely to be of the form "the best estimate of the mishap probability is 10^{-6} and that estimate is good to an order of magnitude." This type of expression of the distribution of a quantity is a natural match to the log normal distribution.

The problem with this approach is that when a log normal prior distribution is combined with data resulting from Bernoulli trials, the posterior distribution is neither a log normal distribution nor any one of the families of distributions accumulated and adored by applied statisticians because of their analytical tractability.

This problem with the log normal distribution may be avoided using a series of approximations. We begin with the log normal prior distribution with a mean representing our best estimate of the mishap probability and a variance expressing the uncertainty in this estimate. This distribution must be approximated by a discrete distribution. (See figure A-1) Interval width is dictated by the slope and magnitude of the probability density function, f(p). The posterior probability density function after r mishaps in n trials is given by

$$h(p_j|r,n) = \frac{p_j\, S_j^{\,r}\,(1 - S_j)^{n-r}}{\sum_{k=1}^{M} p_k\, S_k^r(1 - S_k)^{n-r}} \tag{A-14}$$

where

S_j = the midpoint of the j^{th} interval

p_j = the probability p lies in the j^{th} interval

M = the number of approximating intervals

The posterior mean and variance can be calculated by the equations

$$E(p|r,\, n) = \frac{\sum_{k=1}^{M} p_k\, S_k^{\,r+1}(1 - S_k)^{n-r}}{\sum_{k=1}^{M} p_k\, S_k^r(1 - S_k)^{n-r}} \tag{A-15}$$

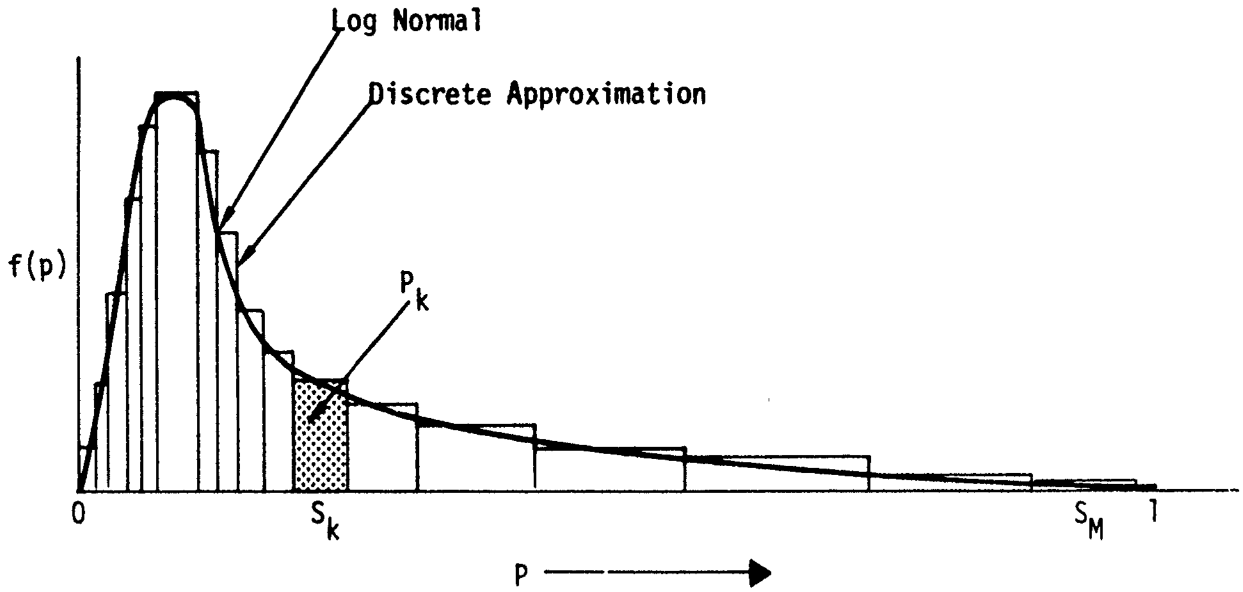

Figure A-1. Discrete Approximation to Log Normal Distribution

$$\mathrm{Var}(p|r, n) = \frac{\sum_{k=1}^{M} p_k{}^{r+2}(1 - s_k)^{n-r}}{\sum_{k=1}^{M} p_k\, s_k^r(1 - s_k)^{n-r}} - [E(p|r, n)]^2 \quad \text{(A-16)}$$

These values may then be used to define a log normal distribution approximating the posterior distribution for mishap probability.

Until this point our discussion has been based on treating mishap occurrences as Bernoulli trials. We now shift to the alternative description of a time (and activity level) dependent Poisson process. For the sake of the following discussion we will assume that a constant activity level exists so that the time dependent process is an appropriate description. The Poisson process assumes that the probability of exactly one mishap in a time interval of length t is proportional to the length of the interval with proportionality constant λ. The probability of exactly r mishaps in an interval of length t is given by

$$P_t(r) = \frac{e^{-\lambda t}(\lambda t)^r}{r!} \tag{A-17}$$

This is equivalent to the statement the time between mishaps is exponentially distributed with the following probability density function

$$f_t(t) = \lambda e^{-\lambda t} \tag{A-18}$$

In either event the gamma distribution is the natural conjugate distribution. The development of a Bayesian formulation for these cases is similar to that for the Bernoulli trial - beta distribution pairing. Similar problems exist with random number generation for this distribution and similar solutions can be employed to overcome them.

Appendix A References

1. Bury, Karl V., Statistical Models in Applied Science, John Wiley & Sons, New York, N.Y., 1973

2. Raiffa, Howard and Robert Schlaifer, Applied Statistical Decision Theory, The M.I.T. Press, Cambridge, Mass., 1961.

3. Winkler, Robert L. and William L. Hays, Statistics: Probability, Inference, and Decision, 2nd Editions, Holt, Rinehart and Winston, New York, N.Y., 1975.

APPENDIX B. FIRE OCCURRENCE DATA

The fire occurrence data were taken from Navy and Marine Corps Fire Loss Experience (Ashore) reports [2] and the corresponding real property data from the Inventory of Military Real Property [3]. Seven years of data with 10,013* loss fires were used.

The fire occurrence data is summarized in Table 1 for the seven years used in the study [1]. The occupancy classifications used for fire reporting [4] provide the classifications used in this table. The real property data are summarized in Table 2 for the same period. The resulting building populations for which a fire frequency, p_i, was determined is given in Table 3. This was accomplished by aggregating fire occurrences from Table 1 with the aggregate areas from Table 2 according to the following equation for p_i:

$$p_i = \frac{N_i(1969) + \ldots + N_i(1975)}{A_i(1969) + \ldots + A_i(1975)} \tag{1}$$

where

p_i = No. Fires/sq.ft./yr. for ith group (i.e., population)

$N_i(xxxx)$ = Total no. of fires in ith group during year xxxx

$A_i(xxxx)$ = Total area of ith group at end of year xxxx in square feet

Table 2 only provides floor areas according to the three digit category code defined in Reference 5. This is the most detailed breakdown that is available for prior years [3].

*This appendix contains a summary of fire occurrence and frequency data developed by Lee and Eguchi [1].

**931 of these fires were, however, inapplicable to the study at hand.

Table 1. Occurrence of Loss Fires at Naval Facilities 1969 - 1975 (Reference 2)

FIRE FREQUENCY CODE	TYPE OF PROPERTY	NUMBER OF FIRES BY YEAR							TOTAL 69 - 75
		1969	1970	1971	1972	1973	1974	1975	
1	AEROSPACE MANUFACTURE, ASSEMBLY, AND MODIFICATION	18	18	16	12	10	14	11	99
2	AUTO GAS SERVICE STATION	1	-	6	1	1	1	2	12
3	BARRACKS	387	346	381	412	546	612	607	3,291
4	BUILDINGS, VACANT	6	4	9	16	18	13	21	87
5	BOQ'S	22	33	23	18	19	13	10	138
6	CAFETERIAS	6	6	3	5	6	3	7	36
7	CHILD CARE CENTERS AND NURSERY	-	2	-	2	1	2	-	7
8	CHURCH, CHAPELS	2	3	7	5	2	4	2	25
9	CLUBS-CPO	5	6	6	10	5	3	2	37
10	CLUBS-EM	16	16	19	8	5	7	13	84
11	CLUBS-OFFICERS	10	10	8	8	7	2	5	50
12	COLD STORAGE AND/OR REFRIGERATION PLANTS	2	2	1	-	-	1	3	9
13	COMMUNICATIONS	21	20	17	21	15	14	15	123
14	DISPENSARIES/DENTAL CLINICS	13	14	15	7	7	19	14	89
15	DRYDOCKS	1	-	1	6	1	2	7	18
16	DWELLINGS-DUPLEX	90	88	76	69	56	58	59	496
17	DWELLINGS-MULTIFAMILY	160	140	146	128	152	127	128	981
18	DWELLINGS-SINGLE FAMILY	125	76	91	96	111	103	132	734

Table 1. Occurrence of Loss Fires at Naval Facilities 1969 - 1975 (Reference 2) (Continued)

FIRE FREQUENCY CODE	TYPE OF PROPERTY	NUMBER OF FIRES BY YEAR							TOTAL 69 - 75
		1969	1970	1971	1972	1973	1974	1975	
19	DWELLINGS-TRAILER	11	10	12	7	9	4	9	62
20	ELECTRONIC DATA PROCESSING	-	3	1	2	3	5	6	20
21	ENGINE TEST CELLS	4	2	4	1	4	2	2	19
22	FLAMMABLE LIQUIDS/GASES-HANDLING AND/OR STORAGE	11	2	4	1	2	3	7	30
23	GARAGE (DWELLING)	6	4	6	11	2	6	8	43
24	HANGERS	16	12	11	15	7	8	25	94
25	HOSPITALS-OTHER THAN WARDS, SURGERY	16	20	9	14	12	7	17	95
26	HOSPITALS-WARDS	47	38	22	10	12	19	8	156
27	KNOWN, BUT NOT CLASSIFIED	40	70	114	55	50	98	67	494
28	LABORATORIES OTHER THAN MEDICAL	14	19	22	18	16	23	14	126
29	LAUNDRIES AND/OR DRY CLEANERS	5	6	2	5	8	7	9	42
30	MESS HALLS AND/OR GALLEYS	25	18	18	19	12	11	14	117
31	MANUFACTURING, PROCESSING, INDUSTRIAL	6	9	10	5	7	1	7	45
32	MISCELLANEOUS SMALL OUTLYING STRUCTURES	20	9	7	19	14	17	16	102
33	OFFICES, ADMINISTRATION, ETC.	61	49	70	59	68	76	73	456
34	MAGAZINE, ORDNANCE AND/OR CHEMICAL STORAGE	4	2	-	1	1	1	1	10

Table 1. Occurrence of Loss Fires at Naval Facilities 1969 - 1975 (Reference 2) (Continued)

FIRE FREQUENCY CODE	TYPE OF PROPERTY	NUMBER OF FIRES BY YEAR							TOTAL 69 - 75
		1969	1970	1971	1972	1973	1974	1975	
35	ORDNANCE MANUFACTURING, ASSEMBLY, AND MODIFICATION	92	44	50	40	40	30	24	320
36	OUTSIDE OR OPEN STORAGE	12	10	4	-	3	3	6	38
37	PIERS-WHARVES	24	9	12	15	8	15	7	90
38	POWER, HEAT, UTILITIES	40	21	27	27	29	28	29	201
39	PRISONER HOUSING AND DETENTION	2	4	6	2	5	3	4	26
40	RECREATION-GYM, ETC.	25	13	21	21	22	21	30	153
41	SCHOOLS-TRAINING	22	18	24	31	23	24	25	167
42	SHIPBUILDING WAYS	1	2	1	-	-	-	1	5
43	SHOPS, HOBBY	5	2	2	1	2	-	1	13
44	SHOPS, MISCELLANEOUS	12	20	17	11	28	27	14	129
45	SHOPS, O AND R	12	7	3	2	3	-	-	27
46	SHOPS, PUBLIC WORKS	9	10	10	15	12	7	4	67
47	STORES, COMMISSARY, EXCHANGES	16	12	13	10	18	13	23	105
48	THEATERS	8	3	5	1	-	-	4	21
49	VEHICLES AND MOBILE EQUIPMENT	103	105	90	113	124	122	114	771
50	WAREHOUSES, STORE HOUSES, SUPPLY	35	32	41	35	27	40	43	253
	TOTALS	1,589	1,369	1,463	1,390	1,533	1,619	1,650	10,613

Table 2. Real Property at Naval Facilities for Selected Category Codes (Reference 3)

CATEGORY	UNITS*	TOTAL AREA							TOTAL
		1969	1970	1971	1972	1973	1974	1975	69 - 75
123	SF	36	36	34	30	---	8	20	164
125	SF	284	289	324	344	401	443	470	2,555
131	SF	3,983	4,042	4,176	4,241	4,092	4,488	4,704	29,726
133	SF	735	683	732	722	614	580	588	4,654
141	SF	3,860	6,465	6,245	6,050	8,005	8,971	9,294	48,890
142	SF	13	7	7	7	3	3	3	43
151	SY	2,577	2,573	2,461	2,371	2,372	2,268	2,287	16,909
152	SY	1,369	1,433	1,458	1,349	1,167	1,271	1,185	9,232
153	SF	**	3,942	**	**	4,413	4,436	4,543	30,334**
155	SF	##415†	##403†	##305	368	251	334	319	2,395
159	SF	##336†	##326†	##248	168	290	283	290	1,941
161	SF	36	2	2	2	4	3	2	51
171	SF	36,252	33,006	30,648	32,654	32,979	33,185	34,106	232,830
211	SF	33,531	33,117	31,301#	29,486	34,024	35,713	36,135	233,307
212	SF	1,147	1,105	1,112	1,175	1,516	1,528	1,612	9,193
213	SF	27,977	26,544	19,432	19,599	24,208	24,657	25,480	167,897
214	SF	8,135	8,167	8,242	8,493	8,727	9,039	9,196	59,999
215	SF	665	671	643	603	548	824	808	4,762
216	SF	2,749	2,706	2,729	2,861	3,258	3,154	3,209	20,666
217	SF	2,846	2,938	2,987	2,869	3,185	3,833	3,418	22,076
218	SF	3,961	3,914	3,733	3,763	4,065	4,211	4,136	27,783
219	SF	10,680	11,648	11,399	11,621	11,774	12,557	12,518	82,197
221	SF	9,522	8,448	8,319	7,646	7,436	7,716	7,706	56,793

*Units are in 1000's; SF = square feet; SY = square yards.
**P-77 values for 69, 71, 72 appear erroneous. Total based on average of remaining years.
#P-77 gave different value, since it seemed inconsistent with 70 & 72 values, 71 values assumed erroneous. Value shown interpolated from 70 & 72.
##Apportioned according to 72--75 data.
†P-77 has units of square yards for these elements. Assumed to be square feet instead.

Table 2. Real Property at Naval Facilities for Selected Category Codes (Reference 3) (Continued)

CATEGORY	UNITS*	TOTAL AREA							
		1969	1970	1971	1972	1973	1974	1975	
222	SF	3,593	3,680	3,709	3,713	3,718	3,775	3,716	25,904
223	SF	681	281	180	**275	369	369	401	2,556
225	SF	173	173	173	185	117	117	117	1,055
226	SF	4,977	4,969	4,845	4,065	3,959	3,812	3,812	30,439
227	SF	499	430	430	670	676	452	464	3,621
228	SF	811	774	370	422	10	22	22	2,431
229	SF	1,016	1,039	1,027	1,195	1,099	1,436	1,509	8,321
310	SF	18,643	18,675	18,681	19,099	18,903	19,587	20,164	133,752
421	SF	30,240	30,541	29,736	29,828	38,667	39,021	38,224	236,257
424	SF	---	---	---	---	34	35	31	#231
431	SF	3,226	3,183	1,463	1,546	2,827	2,316	2,167	21,821
432	SF	1,280	1,309	1,236	1,268	---	---	---	
441	SF	64,645	64,757	62,377	64,234	118,883	116,357	113,047	877,570
442	SF	71,759	71,327	66,413	63,771	---	---	---	
510	SF	8,245	8,558	8,291	8,291	8,466	9,311	10,106	61,268
530	SF	1,609	1,626	1,590	1,589	1,264	1,396	1,418	10,492
540	SF	1,051	1,064	1,090	1,072	1,073	1,064	1,076	7,490
550	SF	3,149	3,260	3,200	3,267	3,275	3,237	3,205	22,593
610	SF	40,112	40,534	39,548	40,753	42,625	42,344	43,030	288,946
620	SF	250	250	246	274	237	217	219	1,693
711	SF	108,070	108,395	105,409	107,545	110,093	111,868	118,952	771,006
712	SF	171	171	165	145	19	0	3	

*Units are in 1000's. SF = square feet.
**P-77 data appears erroneous. Interpolated from 71, 73 data instead.
#Used average for 73--75 for all seven years.

Table 2. Real Property at Naval Facilities for Selected Category Codes (Reference 3) (Continued)

CATEGORY	UNITS*	TOTAL AREA 1969	1970	1971	1972	1973	1974	1975	
714	SF	2,508	2,507	2,459	2,550	3,239	3,750	4,187	21,200
721	SF	5,276	5,270	4,937	5,380	50,640	53,874	56,410	
722	SF	52,665	52,792	50,310	52,931	13,925	10,123	7,414	457,774
723	SF	8,314	8,306	7,915	7,774	1,171	1,173	1,169	
724	SF	14,914	14,977	14,662	14,425	11,314	13,044	12,929	96,265
730	SF	9,471	8,735	8,561	8,942	10,090	10,791	10,944	67,534
740	SF	45,093	45,611	45,478	47,936	50,662	52,425	52,462	339,667
760 #	SF	---	---	---	---	---	#	67	#469
811	SF	2,036	2,045	1,738	1,941	1,873	1,875	1,844	13,402
812	SF	866	872	831	878	709	697	710	6,105
813	SF	---	---	---	---	144	195	203	
821 ##	SF	3,135	3,089	3,054	2,965	1,332	1,763	1,870	17,208
822	SF	---	---	---	---	---	21	24	45
823	SF	6	7	7	10	12	13	13	68
826	SF	---	---	---	---	70	73	74	217
831	SF	185	252	184	179	361	361	371	1,893
832	SF	114	113	123	123	130	125	130	858
833	SF	193	200	173	172	153	**159	**164	1,214
841	SF	538	530	492	515	533	**540	**546	3,694
842	SF	312	305	315	345	285	**290	**295	
844	SF	---	---	---	---	3	6	9	2,285
845	SF	---	---	---	---	40	40	40	
872 +	SF	174	174	11	17	---	6	19	401
890	SF	824	855	821	888	610	507	673	5,178

*Units are in 1000's. SF = square feet.
**P-77 data inconsistent with Ref. 2-11 and prior years. Ref. 2-11 data used.
#Values for 69--74 missing or questionable. Assume 75 value.
##Data used as is; change between 72 & 73 unexplained.
+Data questionable but used as is.

Table 3. Fire Frequency by Category Code

COMBINED FIRE FREQUENCY CODES*	COMBINED CATEGORY CODES*	NO. OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_i
1 Aerospace Manufacture, Assembly, and Modification	221-all Production--Aircraft--Bldgs 221-all Production--Guided Missiles--Bldgs	99	82,697	1.20×10^{-6}
2 Auto Gas Service Station	123-15 Land Vehicle Fueling--Filling Station Bldgs	12	164	7.35×10^{-5}
3 Barracks 5 BOQ'S 30 Mess Halls and/or Galleys 39 Prisoner Housing and Detention	721-all Troop Housing--Bachelor Enlist 722-all Bachelor Housing--Mess Facilities--Bldgs 724-all Bachelor Housing--Officer Housing--Bldgs 725-10 Troop Emergency Housing 730-15 Confinement Facility 740-60 Commissioned Mess--Open 740-64 EM Mess--Open (E-1/E-9) 740-66 Petty Officer Mess--Open 740-70 Mess--Open (E-7/E-9)	3572	574,092	6.22×10^{-6}
4 Buildings, Vacant	Not Used	87	--	--
6 Cafeterias 47 Stores--Commissary, Exchanges	730-13 Issue Retail Clothings/Uniforms 730-30 Bakery 740-01 to-09 Exchanges--Bldgs 740-20 Exchange--Temporary Housing 740-25 to-34 Exchanges, etc.--Bldgs 740-71 Exchanges--Package Stores	141	88,578	1.59×10^{-6}

*Titles for "Fire Codes" from References 2-6 and 2-8: titles for "Category Codes" from Reference 2-10.
**Σ1969 to 1975, area in 1000's of square feet.
#Fire Frequency units are number of fires per year per square foot.

Table 3. Fire Frequency by Category Code (Continued)

COMBINED FIRE FREQUENCY CODES*	COMBINED CATEGORY CODES*	NO. OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_i
7 Child Care Centers and Nursery	730-45 to-60 Dependent Schools 740-74 Child Care Center--Bldgs	7	3,276	2.14×10^{-6}
8 Church--Chapels	740-10, 11 Chapels and Religious Education --Bldgs	25	12,422	2.01×10^{-6}
9 Clubs--CPO 10 Clubs--EM 11 Clubs--Officers	740-63, 69 Clubs	171	19,497	8.77×10^{-6}
12 Cold Storage and/or Refrigeration Plants	431-all Cold Storage--Warehouses	9	21,821	4.12×10^{-7}
13 Communications	131-all Communications Bldgs 133-all Navigation and Traffic Aids--Bldgs	123	34,380	3.58×10^{-6}
14 Dispensaries and Dental Clinics	530-all Laboratories and Clinics Bldgs 540-all Dental Clinics--Bldgs 550-all Dispensaries--Bldgs	89	17,982	4.95×10^{-6}
15 Drydocks (not incorp.into methodology because not a bdlg)	213-10 Maintenance--Ships/Spares--Drydocks	18	33,619	5.35×10^{-7}
16 Dwellings--Duplex 17 Dwellings--Multifamily 18 Dwellings--Single-Family 19 Dwellings--Trailers	711-all Family Housing--Dwellings 712-all Family Housing--Trailers 740-21 Visitor Reception 740-22 Transient Housing	2273	775,667	2.93×10^{-6}

Table 3. Fire Frequency By Category Code (Continued)

COMBINED FIRE FREQUENCY CODE*	COMBINED CATEGORY CODE*	NO. OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_i
20 Electronic Data Processing 33 Offices, Administration, etc.	141-all Land Operational--Bldgs 142-10, 19 Land Operational--Helium Facilities 155-11 Small Craft Berthing-Fleet Landing Bldg 159-20, 30,64 Waterfront Operational--Other Bldgs 610-all Administrative--Offices, Data Processing Bldgs 620-all Administrative--Offices, Data Processing--Underground 740-12 Red Cross, Navy Relief--Bldgs 740-37 Special Services Issue Office 746-76 to 89 Miscel. Admin. Facilities	476	348,816	1.36×10^{-6}
21 Engine Test Cells 24 Hangars	211-05 to-58 Maintenance--Aircraft/Spares--Bldgs 211-60 to 62 211-70 to 77 211-85 to 86	113	233,307	4.84×10^{-7}
22 Flammable Liquids/Gases--Handling and/or Storage	Not Used	30	--	--
23 Garage (Dwelling)	714-all Family Housing--Detached Facilities--Bldgs 723-40 Bachelor Housing--Detached Facilities--Garage 723-60, 77 Troop Housing--Other Detached Bldgs	43	22,024	1.95×10^{-6}
25 Hospitals--Other than Wards, Surgery 26 Hospitals--Wards	510-all Hospitals--Bldgs	251	61,268	4.10×10^{-6}

Table 3. Fire Frequency by Category Code (Continued)

COMBINED FIRE FREQUENCY CODE*	COMBINED CATEGORY CODE*	NO. OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_j
27 Known, But Not Classified	730-10 Fire Stations 730-12 Hose Drying Facility 730-20 Police Stations 740-18 Bank 740-19 Credit Union 760-10 Museum and Memorials--Bldgs 730-65 Fallout Shelter 730-80 to 81 Misc. Bldgs	494	15,552	3.18×10^{-5}
28 Laboratories, Other than Medical	310-all Research, Development, Testing and Evaluation--Bldgs	126	133,752	9.42×10^{-7}
29 Laundries and/or Dry Cleaning	723-30 Bachelor Housing--Detached Facilities--Laundry 730-40 Laundry/Dry Cleaning Plant 740-13 Exchange, Laundry 740-15 Exchange, Dry Cleaning Plant	42	3,655	1.15×10^{-5}
31 Manufacturing, Processing, Industrial	223-10 Production--Ships/Spares--Bldgs 224-all Production--Tank/Automotive--Bldgs 225-all Production--Weapons/Spares--Bldgs 227-all Production--Electronics/Communications Equip.--Bldgs 228-all Production--Misc. Material and Equip.--Bldgs 229-40 to 80 Production--Construction and Misc. Materials--Bldgs	45	17,984	2.50×10^{-6}

Table 3. Fire Frequency by Category Code (Continued)

COMBINED FIRE FREQUENCY CODE*	COMBINED CATEGORY CODE*	NO. OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_f
32 Misc. Small Outlying Structures	125-20 Misc. Pipeline Facilities--Shelter 161-30 Harbor Protection Facilities--Winch House 179-40 Small Arms Range 730-66 to 70 Misc. Structures 723-20 Latrine, Detached 730-25 Gate/Sentry House 730-76 Kennel 730-75 Public Toilet 823-15 Gas Meter Shed 827-10 Transmission Line Shed 843-50 Fire Protect Value Shed 872-20 Guard and Watch Towers	102	3,007	3.39×10^{-5}
34 Magazine, Ordinance and/or Chemical Storage 35 Ordinance Manufacturing, Assembly, and Modification	212-all Maintenance--Guide Missiles--Bldgs 216-all Maintenance--Ammo/Explosives/Toxics--Shops 226-all Production--Ammo/Explosives/Toxics--Bldgs	330	296,557	1.11×10^{-6}
36 Outside Storage	Not Used	38	--	--
37 Piers, Wharves (not incorp. into methodology because not a bldg)	151-all Waterfront Operational--Piers 152-all Waterfront Operational--Wharves	90	235,269	3.82×10^{-7}
38 Power, Heat, Utilities	811-09 and 59 Electric Energy--Bldgs and Util 812-09 Electric Distribution--Bldgs and Shelter 813-10 Switching/Substation--Bldgs and Shelter 821-09 Heating Plant--Bldgs 822-09 Steam/Heat--Bldgs and Shelter 823-09 Gas Generating--Bldgs 826-10 Refrigeration/Air Conditioning Plants--Bldgs 730-78 Dairy Plant	201	52,116	3.86×10^{-6}

Table 3. Fire Frequency by Category Code (Continued)

COMBINED FIRE FREQUENCY CODE**	COMBINED CATEGORY CODE*	NO OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_i
38 Continued	831-09, 14,39 Sewage and Industrial Waste Treatment & Disposal--Bldgs 832-29 Sewage and Industrial Waste Collection--Pumping Stations 833-09 20,40 Solid Waste Handling Facilities --Bldgs 841-09 Water Treatment Facilities--Bldgs 842-09 Water Distribution--Potable--Bldgs 844-10 Water Supply and Storage--Non-potable--Bldgs 845-10 Water Distribution--Nonpotable --Bldgs 890-09, 45,77 Misc. Utilities Plants, Sheds, Shelter, Misc.	201	52,116	3.86×10^{-6}
40 Recreation--Gym, etc. 48 Theaters	730-35, 36 Locker Rooms 740-40 to 56 Recreation and Entertainment--Bldgs 740-75 Aero Club Facility	174	66,934	2.60×10^{-6}
41 Schools--Training	171-all Training--Bldgs	167	232,830	7.17×10^{-7}
42 Shipbuilding Ways	Not Used	5	--	--
43 Shops--Hobby	740-35 Hobby Shop--Amateur Radio 740-36 Hobby Shop--Arts/Crafts 740-38 Hobby Shop--Automotive 740-39 Entertainment Workshop Ctr	13	13,707	9.48×10^{-7}

Table 3. Fire Frequency by Category Code (Continued)

COMBINED FIRE FREQUENCY CODES*	COMBINED CATEGORY CODES*	NO OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_i
44 Shops--Misc. 45 Shops--O&R	213-41 to 77 Maintenance--Ships/Spares--Shops 214-10 to 53 Maintenance--Tank/Automotive--Shops 215-all Maintenance--Weapons/Spares--Shops 217-10 30,77 Maintenance--Weapons/Spares--Shops 218-all Maintenance--Misc. Material and Equip.--Bldgs 740-16 Exchange Maintenance Shop 740-17 Exchange Central Support Facility	156	250,821	6.22×10^{-7}
46 Shops--Public Works	219-10 to 30, 77 Maintenance--Public Works Repair and Operations--Bldgs	67	82,197	8.15×10^{-7}
49 Vehicles and Mobile Equipment	Not Used	771	--	--
50 Warehouses, Storehouses--Supply	153-20 Cargo Handling Facility--Waterfront Transit Shed 153-30 Cargo Handling Facility--Container Operations Bldg 155-21 Small Craft Boathouse 424-10 Weapon Related Battery Storage--Bldgs 441-10 to 35 70to73 General Supply--Storage Dep/Instln--Warehouse 730-77 Personnel Support Storage-Misc. 740-23 Commissary Inc Backup Storage 740-24 Commissary Cold Storage, Det	253	485,158	5.21×10^{-7}
	TOTAL	10,613		

A finer breakdown is required for some categories, particularly the 730 and 740 categories which encompass a plethora of different occupancies. To provide this finer breakdown, the aggregated category areas for prior years was apportioned according to the percentages existing on June 30, 1975. These percentages were calculated using the areas given in the Inventory of Military Real Property[6].

The first digit of the Category Code identifies the nine broad DOD facility classes:

Operational and Training Facilities	100 Series
Maintenance and Production Facilities	200 Series
Research, Development, and Test Facilities	300 Series
Supply Facilities	400 Series
Hospital/Medical Facilities	500 Series
Administrative Facilities	600 Series
Housing and Community Facilities	700 Series
Utilities and Ground Improvement	800 Series
Real Estate	900 Series

Appendix B References

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